Isolated Old Neutron Stars and Axion Stars

Aiichi Iwazaki

Abstract

We show that axionic boson stars collide with isolated old neutron stars with strong magnetic field ($> 10^8$ Gauss) and causes the neutron stars to radiate X ray by heating them. Surface temperatures of such neutron stars becomes $10^5\,\mathrm{K} \sim 10^6\,\mathrm{K}$. We suggest that these are possible candidates for X ray sources observed in ROSAT Survey. We discuss a possible way of identifying such neutron stars. We also point out that the collision generates a burst of monochromatic radiations with frequency given by axion mass.

Axions [1] are one of most plausible candidates of dark matter in the Universe. The axions are produced [2,3] in early Universe mainly by decay of axion strings, decay of axion domain wall or coherent oscillation of axion field. These axions can form [4] coherent axionic boson stars [5] in the present Universe. Namely, some of the axions contract themselves gravitationally to axionic boson stars. We call them simply as axion stars.

In the previous papers [6,7] we have pointed out that when axion stars collide with cold white dwarfs invisible with present observational apparatus, they heat such white dwarfs and make them visible. This heating arises owing to energy deposited by the axion stars to the white dwarfs. That is, a magnetic field of the white dwarfs induces an electric field in the axion stars, which turns to generate an electric current in the white dwarfs. The energy of this electric current is dissipated, owing to finite electric conductivity of the white dwarfs. Consequently the white dwarfs gain thermal energy, that is, the energy of the axion stars is transformed to the thermal energy of the white dwarfs by the collision. As a result, old white dwarfs regain their brightness. This thermalization of the axion energy under the magnetic field is a phenomenon similar to one arising in a cavity proposed for detection of the axion by Sikivie [8].

In this letter we point out that cold neutron stars (NSs) also regain brightness by collision with axion stars. As a result these neutron stars becomes detectable with X ray observation. In particular, isolated old neutron stars become to emit X ray with this mechanism just as those accreting gas of interstellar medium. Hence they are possible candidates for X ray sources detected in ROSAT ALL-Sky Survey. Since both values of strength of magnetic field and electric conductivity are extremely large in the case of NS, energy dissipation of axion star proceeds very rapidly so that the collision would be observed as an explosion generating a blast of wind. Since electric currents induced in NS by the collision are oscillating with single frequency, a burst of monochromatic radiations is also produced.

We calculate luminosity of such NSs and estimate how many they exist in the neighborhood of the sun. We show that old NSs gain so much energies with the collision as for their surface temperatures to increase up to 10^5K $\sim$ 10^6K. Furthermore, we show that there may be one or more such NSs within the distance of 1Kpc around the sun, assuming dark matter being dominated by axion stars. However, the precise number depends on several unknown parameters, e.g. mass of axion stars, collision parameters between axion star and NS, etc. The masses of the axion stars in which we are interested are assumed such as $M_a = 10^{-11} M_\odot \sim 10^{-13} M_\odot$, which have been favored according to arguments of the generation mechanism of axion stars by Kolb and Tkachev [4]

Let us first explain briefly axionic boson stars [6] and then we explain [7] how they dissipate their energies in NS. In general, boson stars are composed of coherent bosons bounded gravitationally, which are described by a solution of a corresponding boson field equation coupled with gravity. In our case axions are such bosons with mass m_a and are represented by a real scalar field a. Axion stars are coherent bound states of the boson and are characterized by their mass M_a or radius R_a, which are related with each other. Explicitly they are represented approximately by

$$a = f_{PQ} a_0 \sin(m_a t) \exp(-r/R_a)\,, \tag{1}$$

where t (r) is the time (radial) coordinate and f_{PQ} is the decay constant of the axion. The value of f_{PQ} is constrained from cosmological and astrophysical considerations [3] such as 10^{10} GeV $< f_{PQ} < 10^{12}$ GeV. Here dimensionless amplitude, a_0 in eq(1) is represented explicitely in terms of the radius, R_a in the limit of small mass (e.g. $\sim 10^{-12} M_\odot$) of the axion star [6],

$$a_0 = 1.73 \times 10^{-8} \frac{(10^8\,\mathrm{cm})^2}{R_a^2} \frac{10^{-5}\,\mathrm{eV}}{m_a} \quad . \tag{2}$$

In the same limit we have found [6] a simple relation between the mass M_a and the radius R_a of the axion star,

$$M_a = 6.4\,\frac{m_{pl}^2}{m_a^2 R_a}\,, \tag{3}$$

with Planck mass m_{pl}. Numerically, $R_a = 1.6 \times 10^8\, M_{12}^{-1}\, m_5^{-2}\,\mathrm{cm}$ where $M_{12} \equiv M_a/10^{-12}\, M_\odot$ and $m_5 \equiv m_a/10^{-5}\,\mathrm{eV}$. A similar formula holds even without the limit but with a minor modification of numerical coefficient. It turns out that the axionic boson stars are "oscillating " with the frequency of $m_a/2\pi$ [9]. It has been shown that there are no physically relevant, "static", axionic boson stars. This property is specific in real scalar field. Static solutions of complex boson field representing boson stars are well known to exist [5].

These axion stars induce electric fields under a magnetic field; the magnetic field is supposed to be associated with neutron star in this paper. This can be easily seen by taking account of a following interaction term between axion and electromagnetic field,

$$L_{a\gamma\gamma} = c\alpha a \vec{E} \cdot \vec{B} / f_{PQ} \pi \tag{4}$$

with $\alpha = 1/137$, where $\vec{E}$ and $\vec{B}$ are electric and magnetic fields respectively. The value of c depends on the axion models [10,11]; typically it is of order 1. It follows from this interaction that Gauss's law is modified such as

$$\vec{\partial}\vec{E} = -c\alpha\vec{\partial}(a\vec{B})/f_{PQ}\pi + \text{"matter"} \tag{5}$$

where the last term, "matter", denotes contributions from ordinary matter. The first term on the right hand side represents an electric charge density formed by axion field under external magnetic field $\vec{B}$ [12]. It is interesting that the axion field can induces the electric charge, inspite of the field itself being neutral.

We find that axion star induces an electric field, $\vec{E_a} = -c\alpha a\vec{B}/f_{PQ}\pi$, under the magnetic field. This field is oscillating since the field a is oscillating, and induces oscillating electric currents in NS. Accordingly, monochromatic radiations are emitted. Note that the radius R_a of the axion star is much larger than the radius, $R_n \sim 10^6$cm, of neutron star; $R_a = 10^7\,\text{cm} \sim 10^9\,\text{cm}$ for axion stars with mass, $M_a = 10^{-11}\,M_\odot \sim 10^{-13}\,M_\odot$. Hence the electric field induced at any place in the axion star does not necessarily generate electric current. Electric current is only induced in electric conducting medium such as NS. Thus only a part of the axion star contacting NS generates electric current in NS. This electric currents, $J_a = \sigma E_a$, are very strong since the electric conductivity, σ, is quite high in NS (for example, $\sigma \sim 10^{26}$/s in crystallized envelope of NS [13]). Accordingly, the rate of the energy dissipation of the current is very large. Since the energy of the current is supplied by the axion star, the energy dissipation of the axion star itself proceeds very rapidly. Actually we find that axion stars dissipate their energies so rapidly that they evapolate quite soon simply when they touch with NS. It may be observed as an explosion generating a burst of monochromatic radiations as well as a blast of wind. In this way, the axion star releases the entire energy ($\sim 10^{42}$ erg) in NS. The energy heats up cold NS. Consequently such a NS becomes bright again.

Now we estimate the rate of the energy dissipation with use of Ohm's law. We consider the circumstance that axion star collides with NS, which gains thermal energy inside of the axion star. Taking account of the fact that the radius R_a of the axion star is much larger than that of NS, we calculate Joule's heat W produced in NS,

$$W = \int_{r<R_n} \sigma E_a^2 \, dx^3 \,, \tag{6}$$

$$= \sigma\alpha^2 c^2 B^2 R_a^3 a_0^2/8\pi\,, \tag{7}$$

$$= 4c^2 \times 10^{54}\,\mathrm{erg/s}\,\frac{\sigma}{10^{26}/s}\,\frac{M}{10^{-12}\,M_\odot}\,\frac{B^2}{(10^{12}\,\mathrm{G})^2}\,, \tag{8}$$

with $c \sim 1$, where we have used eqs(1)$\sim$(3) and have supposed that strength of magnetic field of NS is typically given by 10^{12} Gauss.

This large rate of the energy dissipation implies rapid evapolation of the axion star when both two stars collide. Actually, since the energy dissipation only arises in a part of the axion star contacting NS and the energy stored in the part is only about $M_a(R_n/R_a)^3 \sim 10^{36}\,\mathrm{erg} M_{12}^4 m_5^6$, formally it takes $10^{36}/10^{54} = 10^{-18}$ second for the dissipation of the energy. Therefore we find that the rapid evapolation of the axion energy arises even if NS possesses much weak magnetic field such as 10^8G; the strength of this order of magnetic field is expected to be associated with old NSs. Probably, such rapid dissipation of the energy may be seen as an explosion of envelope of NS [14]. It would generates a blast of wind, which subsequently collides with interstellar medium. Thus the medium emits radiations with various frequencies as a burst.

We should mention that since electric currents induced in NS are oscillating with frequency $m_a/2\pi$, the currents generate radiations with the frequency. Thus we expect that a burst of photons with energy m_a of axion mass is produced by the collision. This detection of the radiations is strong indication of the occurrence of such a collision. Furthermore, we can determine the mass as well as the existence of the axion by the detection of the burst.

After axion star collides with NS, it seems that axion star simply passes NS only with loss of a part of its energy through the dissipation mentioned above. But it is reasonable to consider that it is trapped to NS, because the mass of the axion star is much smaller than that of the NS. Both kinetic energy and angular momentum of axion star would be dissipated through the above mechanism [7]. When the axion star is trapped, the entire energy of the axion star is dissipated after all.

Hereafter, we assume that the entire energy of the axion star is dissipated when it collides with NS. Hence, the energy gained by NS with the collision is given by the mass of the axion star, $M_a = 10^{41}\,\mathrm{erg} \sim 10^{43}\,\mathrm{erg}$. This energy heats up cold NSs and makes them become bright again.

In order to calculate roughly how temperature of such NSs rises up, we use heat capacity of free nucleons composing the NSs for simplicity. Assuming that the density of the NS is low enough for non-relativistic approximation to be valid, we may use the following formula of thermal energy [15] in the NS,

$$U = 6 \times 10^{47}\,\mathrm{erg}\,(M/M_\odot)\,(\rho/\rho_n)^{-2/3}\,(T/10^9\,\mathrm{K})^2, \tag{9}$$

with $\rho_n = 2.8 \times 10^{14}\,\mathrm{g\ cm^{-3}}$ being density of nucleon, where T, M and ρ denote the core temperature, mass and average density of the NS, respectively. Explicitly, we take the numerical parameters, $M = 1.5\,M_\odot$ and $\rho = 7 \times 10^{14}\,\mathrm{g\ cm^{-3}}$, which implies that the radius of the neutron star is given by $R = 10^6$ cm.

Since old NSs with their ages $\sim 10^{10}$ years have lost almost all thermal energies, the energy deposited by the axion star is main thermal energy by which their temperature is determined.

$$T \simeq 8.6 \times 10^6\mathrm{K}, \quad 2 \times 10^6\mathrm{K}, \quad \text{and} \quad 6 \times 10^5\mathrm{K} \tag{10}$$

for

$$M = 10^{-11}\,M_\odot, \quad 10^{-12}\,M_\odot, \quad \text{and} \quad 10^{-13}\,M_\odot \quad \text{respectively.} \tag{11}$$

This temperature is core temperature of NS. In order to obtain luminosity of NS, we need to know surface temperature. The temperature depends on not only the core temperature but also composition of atmosphere, or envelope of the NS. Here we use a model [16] in which an improved equation of state of the envelope is adopted; it is assumed in the model that the envelope is composed only of iron. Then we can find surface temperatures, T_s,

$$T_s \simeq 2.8 \times 10^5\mathrm{K}, \quad 1.4 \times 10^5\mathrm{K}, \quad \text{and} \quad 9 \times 10^4\mathrm{K} \tag{12}$$

with which luminosity of NS is obtained,

$$L = 7 \times 10^{36}\,\mathrm{erg/s}\,(T_s/10^7\mathrm{K})^4 \tag{13}$$

$$\simeq 4.3 \times 10^{30}\,\mathrm{erg/s}, \quad 2.7 \times 10^{29}\,\mathrm{erg/s}, \quad \text{and} \quad 4.6 \times 10^{28}\,\mathrm{erg/s} \tag{14}$$

corresponding to the masses in eq(11) of the axion stars, respectively. From these luminosities we can estimate roughly a period of NSs keeping this brightness, that is the period of NSs exhausting the energies deposited by the axion stars. It is approximately given by $M_a/L \simeq 10^5$ years for any cases mentioned above. This value is a lower limit of the period. Actual time scale for NS to exhaust the energy deposited is longer than 10^5 years. But we may think the value as a typical time scale for which NS maintains its brightness.

We have obtained the above values of the surface temperatures by assuming strength of surface gravity and composition of NS's envelope. The surface gravity is determined by the parameters we have used; $M = 1.5M_\odot$ and $R = 10^6$ cm. On the other hand, NS's envelope has been assumed to be composed only of iron. If the surface gravity is stronger or there are few contamination of H or He in the envelope [16], the surface temperatures become larger than the values estimated above. Thus we may expect that real temperatures range roughly in $10^5\,\mathrm{K} \sim 10^6\,\mathrm{K}$. Therefore, these NSs may be possible candidates of X ray sources observed in ROSAT Survey.

Although the luminosities obtained are sufficiently large for observation, it is hard to detect such NSs if the number of the NSs present in our neighborhood is quite few. Thus we wish to estimate how many such bright NSs are present in our galaxy. Especially we are concerned with the number of the NSs located within the distance of 1 Kpc around the sun.

In order to estimate the quantities, we need to know both numbers of cold NSs and of axion stars present in our galaxy. The number of the NSs has been guessed on the basis of present rate of appearance of supernova in a galaxy and abundance of heavy elements in our galaxy. The number has been estimated to be of the order of 10^9 in our galaxy. On the other hand the number of axion stars is completely unknown. However, we may assume that the halo is composed mainly of the axion stars, because the axions are plausible candidates of the dark matter. Using these assumptions, we can estimate the number of the NSs having collided with axion stars and having not yet lost their brightness.

Since local density ρ_a of halo is given approximately such that $\rho_a = 0.5 \times 10^{-24}\text{g cm}^{-3}$ [3], we find that the number density n_a of axion stars is, $n_a = \rho \times (1\text{Kpc})^3/M_a \sim 6 \times 10^{18}/M_{12}$ per 1Kpc^3. Under the assumptions that cross section of the collision between a NS and an axion star is naively given by the geometrical cross section of axion star, πR_a^2 and that velocity of axion stars in halo is given typically by 3×10^7 cm/s, we calculate the number of the collisions per 1Kpc^3 and per year,

$$R_c = n_a \times n_{ns} \times \pi R_a^2 v \times 1\,\text{year} \simeq 10^{-8} \times \frac{1}{M_{12}^3 m_5^4} \text{ per year and per } 1\text{Kpc}^3 \tag{15}$$

where n_{ns} denotes the number of NSs in the volume of 1Kpc^3. Here we have assumed uniform distribution of 10^9 NSs in the disk of our galaxy. This R_c represents the production rate of NSs heated by the collision. On the other hand, life time for such NSs to maintain brightness eq(13) is about 10^5 years. Thus, the number of the bright NSs produced for 10^5 years by the collision is $\simeq 10^{-3}/M_{12}^3 m_5^4$ in a local region with its volume 1Kpc^3 around the sun. In other words there are $\sim 1/M_{12}^3 m_5^4$ NSs in our galaxy. The result suggests that if the mass of the axion star is smaller than $10^{-13}M_\odot$, the number of NSs within the volume is larger than 1 and hence such NSs may be detectable. Here we have restricted that $m_a > 10^{-5}$ eV.

In the estimation of R_c we have assumed a naive geometrical cross section of the axion star as its collision cross section with NS. But since NS and axion star interacts gravitationally with each other, its collision cross section is larger than the naive one. Since the rate R_c becomes larger as the cross section increase more, it is plausible that real number of the existing NSs having become bright again is larger than the value obtained above.

Therefore we conclude that if the mass of the axion star colliding NS is smaller than $10^{-13}M_\odot$, or collision cross section is much larger than the geometrical one $\sim 10^8\, M_{12}^{-1}\, m_5^2$ cm of the axion star, the number of the NSs present within the distance of 1Kpc around the sun is large enough for observation. Since surface temperatures of these NSs are of the order $10^5\text{K} \sim 10^6\text{K}$, they are observable as X ray sources. In the derivation of this conclusion, significant assumption is that halo is composed mainly of axion stars. On this point, recent gravitational microlense observation [17] indicates that a half of the halo is composed of objects with mass $0.1\,M_{\odot} \sim 0.5\,M_{\odot}$. If this is true, in order to obtain the conclusion we need the assumption that the other half of the halo is be composed of axion stars.

Finally we discuss how we should identify NSs as ones heated by axion stars. Especially, we wish to distinguish them from NSs which emit X ray by accreting gas of interstellar medium. The latter is located in a region where density of the gas is relatively large, while the former is located even in a region without any gas. Furthermore, the NS accreting the gas must have very low velocity ($\sim$ 10km/s), while the NS heated by axion star may have relatively high velocity for instance $\sim$ 200km/s. Accordingly, if a X ray source is located in a region with few interstellar medium and has a relatively high velocity, it may be identified as a NS heated by axion star. As we have pointed out, the collision between NS and axion star would be seen as an explosion generating a blast of wind as well as a burst of monochromatic radiations Thus the NS produced recently by the collision would have a cloud of gas surrounding it, which was carried by the wind. This kind of the cloud is not present around middle aged neutron stars, which also are candidates of X ray sources. Hence if we detect such a cloud around a X ray source, the source is strong candidate of the NS heated by axion star.

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